Major Technological Innovations Introduced in the

Large Antennas of the Deep Space Network

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The NASA Deep Space Network (DSN) is the largest and most sensitive scientific, telecommunications and radio navigation network in the world. Its principal responsibilities are to provide communications, tracking, and science services to most of the world's spacecraft that travel beyond low Earth orbit. The network consists of three Deep Space Communications Complexes which are located on three continents: at Goldstone in Southern California's Mojave Desert; near Madrid Spain; and near Canberra Australia. Each of the three complexes consists of multiple large antennas equipped with ultra sensitive receiving systems. A centralized Signal Processing Center (SPC) remotely controls the antennas, generates and transmits spacecraft commands, and receives and processes the spacecraft telemetry.

The main features of the complex are the large parabolic dish antennas and their support structures. Although their diameters and mountings differ, all antennas employ a Cassegrainian type feed system. Each antenna dish surface is constructed of precision-shaped aluminum panels that are secured to an open steel framework. The first antenna built for the DSN was a 26-meter dish that operated at L-band (960 MHz) in support of the Pioneer 3 and 4 missions. Throughout its history, the DSN has introduced many technological innovations in the design and construction of large antennas. This paper details many of these major innovations and speculates on the future of the DSN. The complete history is available in a recent book by Imbriale [1].

Technology Drivers

The prime mission of the DSN is to receive extremely weak signals over vast interplanetary distances. A key element of the telecommunications link performance is the received power signal-to-noise ratio, which is given by

$$S/N \approx \frac{P_T G_T G_R}{4\pi R^2 N} = \frac{4\pi P_T A_T A_R}{\lambda^2 R^2 kBT_s} \qquad (1)$$

P_T is the spacecraft transmit power, G_T is the gain and A_T is the effective area of the transmit (spacecraft) antenna, G_R is the gain and A_R the effective areas of the receive ground antennas, N is the total noise, R the distance to the spacecraft, T_s

the receive system noise temperature, λ the wavelength, B is the bandwidth, and k is Boltzman's constant. To do its part effectively, the ground antenna system must maximize the ratio of received signal to the receiving system noise power, which is measured by an antenna figure of merit defined as the ratio of antenna gain (or equivalently effective area) to system noise temperature (G/T). Thus to maximize the G/T for a given antenna size and frequency of operation, it is necessary to both maximize the antenna gain and minimize the total system noise temperature.

The receive temperature consists primarily of the antenna feed system and amplifier contributions. Since the amplifiers used in the DSN are cryogenically cooled and have very low noise temperatures (as low as 2-3 K for the best performing masers) it is critical to minimize the noise temperature contribution of the antenna.

Techniques for maximizing the antenna gain and aperture efficiency of reflector antennas involve control of the illumination function. By definition, a feed system, which uniformly illuminates the antenna aperture with the proper polarization and has no spillover energy or other losses, possesses 100% aperture efficiency. In practice, however, some spillover is present due to the finite size of the feed illuminating a single reflector system or the subreflector illuminating the main reflector of a dual reflector system. One key result of this spillover is a thermal noise contribution from the physically hot ground. Clearly, then, an ideal feed system has a very rapid cutoff at the reflector edge region, thereby maintaining relatively uniform reflector illumination while at the same time minimizing spillover energy.

The earliest designs used a two-reflector Cassegrainian system in which the main reflector is a paraboloid and the subreflector is a hyperboloid. Subsequent designs used dual-shaped designs, which offer higher efficiency for the same size aperture.

Surface accuracy is also an important parameter in determining effective aperture area and for high frequency operation the RMS surface error must be an extremely small fraction of the reflector diameter.

Antennas of the DSN

The initial DSN antenna (~1958) was a 26-meter L-band Cassegrainian design fed by a pyramidal horn with a turnstile junction used as a polarizer. A second 26-meter antenna was built in 1962 and in 1964 the antenna was converted to S-band and utilized a dual mode conical (Potter) horn. Subsequently (~1976) it was upgraded to support simultaneous S- and X-band using a reflex-dichroic feed system. In 1979 the diameter was enlarged from 26-meters to 34-meters.

The first 64-meter was completed in 1966 and was a physical scale up of the 26 meter antenna. Initial operation was at S-band. In 1968 an X-band feed cone was installed. As the need developed for rapidly changing feed cones, the standard feed-cone support structure was replaced with a structure capable of supporting three fixed feed cones. The subreflector was modified to permit rapid changing of feed cones by rotating an asymmetrically truncated subreflector about its symmetric axis, and pointing it toward the feed. Simultaneous multi-frequency was provided by a reflex-dichroic feed system. In support of the Voyager encounter at Neptune, additional performance was realized by increasing the size of the antenna to 70-meters, utilizing dual shaped optics, and improving the main-reflector surface accuracy through the use of high-precision panels. The potential use of Ka-band on the 70-meter was demonstrated through R and D experiments using an Array Feed Compensation System (AFCS) in conjunction with a Deformable Flat Plate (DFP). These technologies were needed to compensate for the gravity-induced deformations as a function of elevation. In 2000 X-band uplink capability was added using a two-frequency pass band dichroic plate.

In 1982 a new 34-meter design that used a common aperture feed horn (for simultaneous S- and X-band transmit and receive) as well as dual shaped optics designed for optimum G/T was introduced into the DSN.

Early in 1990 a new Research and Development antenna was fabricated and tested as a precursor to introducing beam waveguide antennas (BWG) and Ka-band frequencies into the DSN. There are a number of advantages to feeding a large ground station antenna via a beam-waveguide system rather than directly placing the feed at the focal point of a dual-reflector antenna. In a BWG system, the feed horn and support equipment are placed in a stationary room below the antenna, and the energy is guided from the feed horn to the subreflector, using a system of reflecting mirrors. Thus, significant simplifications are possible in the design of high-power water-cooled transmitters and low-noise cryogenic amplifiers, since these systems do not have to tilt as in normally fed dual-reflector antennas. Furthermore, these systems and other components can be placed in a more accessible location, enabling easier servicing and repair. In addition, the losses associated with rain on the feed-horn cover are eliminated because the feed horn is sheltered from weather.

The R and D antenna was initially designed for X- and Ka-bands but was subsequently upgraded to include S-band. The antenna supports simultaneous S- and X-band or simultaneous X- and Ka-band frequencies. The initial simultaneous X- and Ka-band system used a frequency-selective surface (FSS) to separate the X-band and Ka-band signals. This approach has the advantage of requiring relatively simple X- and Ka-band feed horns. Disadvantages include the real estate required for the two feed horns, the need for separate dewars for the X- and Ka-band LNAs, and the noise added due to scattering from the FSS used to diplex the signals. To overcome these disadvantages, a single feed horn that accommodates all the required frequencies in one package was developed. This feed horn provides for the Ka-band receive signal as well as diplexing the X-band transmit and receive signals. A monopulse tracking coupler is also utilized for Ka-band pointing. This feed system is compact and has low noise relative to separating the X- and Ka-band signals with an FSS. Also, a single, but larger dewar, is used to house all of the LNAs.

Based upon the knowledge gained with this antenna, operational BWG antennas were included in the network.

Also during the early 1990's the Jet Propulsion Laboratory designed, constructed, and tested a Technology Demonstration Facility (TDF), consisting of two 34-m diameter BWG antennas and associated subsystems. This was part of a study to explore the engineering aspects of combining transmitted pulses in position, time, and phase from independent radar systems, as well as to determine the applicability of using a beam-waveguide system for high-power applications in large ground station antennas.

The RF design of large antennas has been a great success story. The designs have developed and matured to a point that only very small improvements in performance are possible, especially at S-band or X-band. Virtually the only option available to improve performance at S- and X-band would be to use a clear aperture antenna such as the Green Bank Telescope [2]. This is a very expensive and mechanically complicated alternative that only gains a fraction of a dB in gain (or possibly 1 dB in G/T). Whereas a clear aperture antenna is valuable for Radio Astronomy, it would be far more cost effective for DSN use to just make the blocked aperture larger. At Ka-band there is room for improvements in the surface accuracy or in the gravity deformation performance.

If the DSN would like a substantial improvement in performance (10 to 100 times the current G/T), it will have to follow the lead of the next generation of large radio telescopes which all plan to use large numbers of smaller antennas.

References:

[1] William A. Imbriale, *Large Antennas of the Deep Space Network*, JPL Publication 02-6, Jet Propulsion Laboratory, Pasadena, California, 2002 (in press) also posted at http://descanso.jpl.nasa.gov/index_ext.html

[2] 100-meter Green Bank Telescope [National Radio Astronomy Website], http://info.gb.nrao.edu/GBT/GBT.html